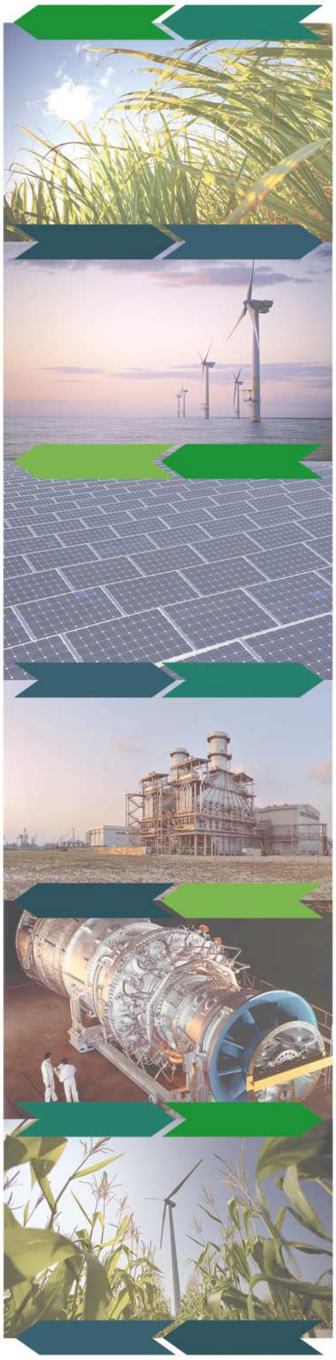
NAVIGATING THE ROADMAP FOR CLEAN, SECURE AND EFFICIENT ENERGY INNOVATION



*Issue Paper on*

# Hybrid Modelling: Linking and Integrating Top-Down and Bottom-Up Models

## Issue Paper prepared for the Modelling Workshop “Top-Down Bottom-Up Hybrid Modelling” November 24-25, 2016 at NTNU Trondheim


**Authors:** Franziska Holz (DIW Berlin), Dawud Ansari (DIW Berlin), Ruud Egging (NTNU), Per Ivar Helgesen (NTNU)



November 2016

A report compiled within the H2020 project SET-Nav (work package 10, deliverable D10.1)

www.set-nav.eu

**Project Coordinator:** Technische Universität Wien (TU Wien)

**Work Package Coordinator:** Deutsches Institut für Wirtschaftsforschung (DIW Berlin)

SET-Nav
Strategic Energy Roadmap

The project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement no. 691843 (SET-Nav).

Project coordinator:

Gustav Resch

Technische Universität Wien (TU Wien), Institute of Energy Systems and Electrical Drives, Energy Economics Group (EEG)

Address: Gusshausstrasse 25/370-3, A-1040 Vienna, Austria

Phone: +43 1 58801 370354
Fax: +43 1 58801 370397
Email: resch@eeg.tuwien.ac.at
Web: www.eeg.tuwien.ac.at

Dissemination leader:

Prof. John Psarras, Haris Doukas (Project Web)

National Technical University of Athens (NTUA-EPU)

Address: 9, Iroon Polytechniou str., 15780, Zografou, Athens, Greece

Phone: +30 210 7722083
Fax: +30 210 7723550
Email: h_doukas@epu.ntua.gr
Web: http://www.epu.ntua.gr

Lead authors of this report:

Franziska Holz (DIW Berlin)

Email: fholz@diw.de

Web: www.diw.de/en/diw_01.c.100376.en/about_us/people_at_diw_berlin/staff/staff.html?id=45&sprache=en ,

Ruud Egging (NTNU)

Email: ruud.egging@iot.ntnu.no
Web: http://www.ntnu.edu/employees/rudolfge

# Table of Contents

# 1 Introduction

In the scientific community two contrasting streams of modelling techniques for analysing energy-system-related issues have been developed: the bottom-up, sectoral, or engineering approach, and the top-down, macroeconomic approach (Wene, 1996; Hourcade et al., 2006). The sectoral approach aims at developing bottom-up models through descriptions of technologic aspects of the energy system. In contrast, the traditional macroeconomic approach is to describe the economy as a whole and to emphasize the possibilities to substitute different production factors in order to optimize social welfare. The two approaches differ considerably in their identification of the relevant system and may therefore produce different guidance for policy-makers. However, as tools to support decision making and policy development, these modelling approaches complement each other. Therefore, linking bottom-up sectoral (engineering) models with (macroeconomic) top-down models can be an important contribution for designing energy systems compatible with sustainable economic growth. *Hybrid modelling* is used to indicate a mix of both modelling perspectives with the expectation that "the whole" should exceed the sum of its parts: integrating aspects and functionality from top-down and bottom-up modelling approaches results in "hybrid" models, which may provide more insight than the individual models could on their own. This papers considers two types of linking. *Soft-linking* models means that the "user" controls the data exchange between the models. *Hard-linking* models means that the data exchange is automated. Integrated, hybrid models combine perspectives and characteristics, *modelling functionality*, for both bottom-up and top-down approaches

# 2 Model Linking

A linking of models is achieved through iterations with information exchange between the models. The first example of linked energy-economy models was reported by Hoffman and Jorgenson (1977). They linked the Brookhaven Energy System Optimisation Model (BESOM) with a general equilibrium model and, later, with an input-output model. During the following decades, several studies have linked economic and systems engineering models, initially these links were "soft", i.e., the information transfer between the models was directly controlled by the user. It becomes necessary to categorize different types of linkages (Figure 1).

**Soft-linking** is a necessary starting point in order to test different modelling and linking approaches. By soft-linking, we mean that processing and transfer of information is controlled by the user. The user evaluates results from the models and decides if and how the inputs of each model should be modified to bring the two sets of results more in line with each other, i.e., how to make the input assumptions and results of the models consistent with each other, i.e., *converge*.

The first example of **hard-linking** of energy-economy models was reported by Manne and Wene (1992). By hard-linking, we mean that all information processing and transfer is formalized and usually handled by computer programs. In areas where the models overlap, an algorithm may be used to negotiate input data and results. Usually one model is given control over certain results, and the other model is set up to reproduce the same results, typically with a different aggregation level.

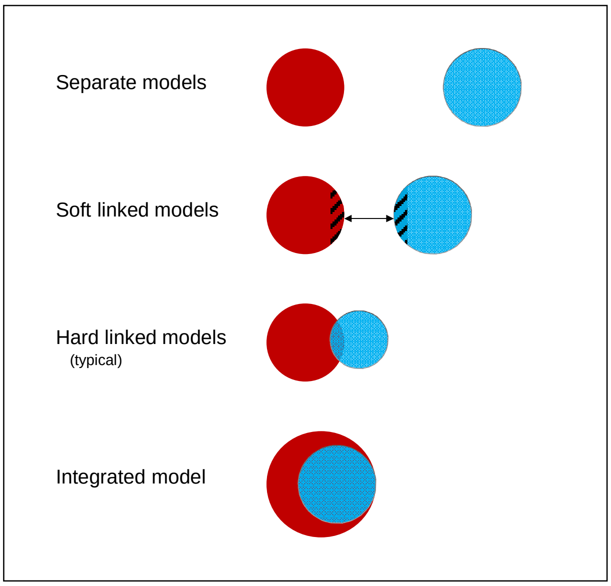



**Figure 1: Different types of linking**
Source: Helgesen (2013)

The advantages of soft-linking can be summarized as practicality, transparency, and learning, while the advantages of hard-linking are efficiency, scalability, and control. Soft-linking seems the most reasonable starting point for linking models based on different approaches. Initial investments in computer programming are kept low, and the modellers can obtain results for evaluation and learning fairly quickly. But for reasons of efficiency, hard-linking is the preferred end product: As the number of model runs increases, and more model users become involved, more resources are needed to retain the quality of soft-linked models than for hard-linked ones.

A subsequent step after hard-linking could be to **integrate the models**. The distinction between hard-linking and integration can be less clear. Integrated models are run in one common format with a single model formulation, instead of exchanging information between separate models. However, when an integrated model is solved using a decomposition approach, one may observe a data exchange between the partial problems which is very much alike that in hard-linked models. Still, we should look at such a model as an integrated model and not as a hard-linked model.

Integration of the models is not always a desired next step. There are substantial benefits from keeping the models stand-alone, such as development, maintenance, diverse foci and relative strengths of the models, and allowing for different levels of spatial and temporal disaggregation.

A slightly different classification of approaches – based on different model types instead of linking types – is given in Böhringer and Rutherford (2008, 2009). They define three broad categories of hybrid modelling efforts that aim to combine bottom-up engineering models with top-down economic models:

a) Linking between individual, “equally important”, stand-alone models (typically soft-links)

b) Linking where one of the models dominates and is complemented by the other one. The sub-dominant model is usually implemented in a reduced form. This is a typical model constellation that enables hard-links between the models (although hard-linking can also be implemented between individual stand-alone models).

c) Combining bottom-up and top-down characteristics directly in an integrated model, possibly belonging to a more general model class.

In the following, we will continue to use the distinction between soft- and hard-linking (Sections 4 and 5). There are various types of hybrid models. Some combine different modules – which may be optimization or equilibrium models (Figure 2). Often, specialized modules are combined in order to produce projections for different scenario assumptions.

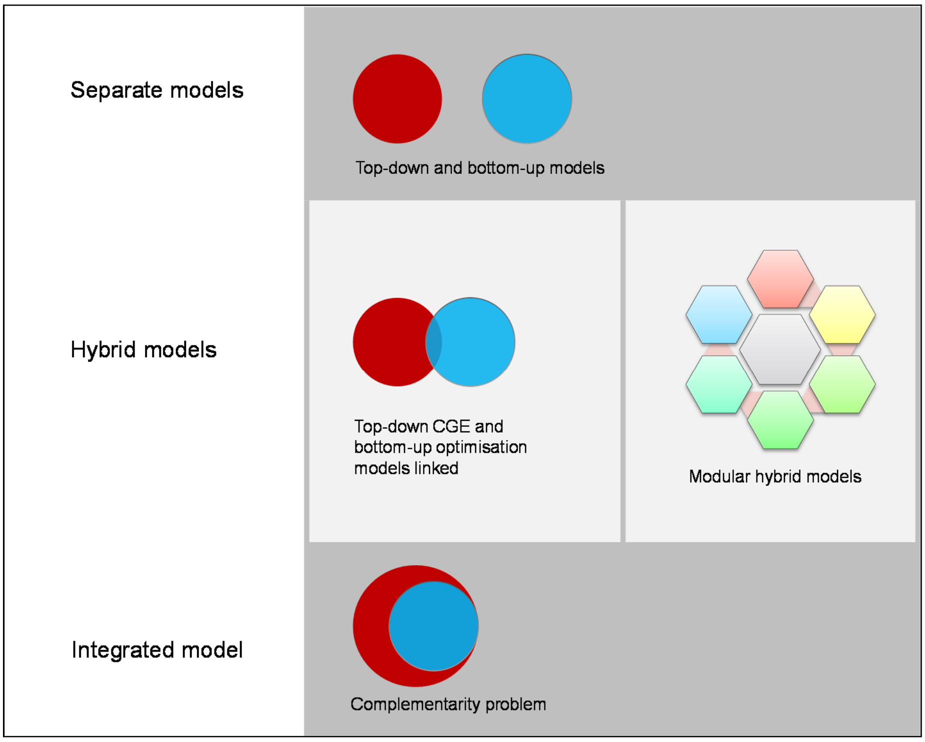



**Figure 2: Hybrid models**

Source: Helgesen (2013)

# 3 The Starting Points: Computational General Equilibrium and Partial Models

## 3.1 Top-down models

Even though they are often regarded as "macroeconomic" models, Computable General Equilibrium (CGE) models are based on a microeconomic framework: Consumers demand goods in order to maximize utility, and producers supply goods under profit maximization. The first successful implementation of a computable general equilibrium model was made in 1960 by Leif Johansen (Johansen, 1960; Jorgenson, 1982).

Most contemporary CGE models belong to the class of complementarity problems. This class includes various nonlinear and non-convex problems, but also the simpler linear and quadratic programming problems. As such, a linear or quadratic program can be cast as a complementarity problem, and thereby easily integrated in another complementarity problem.[1]

[1] The class of complementarity problems is included in the classes of variational inequality problems (VI) and Quasi-variational inequality problems (QVI) (Facchinei and Pang 2003; Gabriel et al. 2012). A complementarity problem can be modelled as (or, *reduced to*) an optimization problem if the Jacobi matrix is symmetric. If this is not the case,

## 3.2 Bottom-up models

Since (convex) optimization problems (of the bottom-up engineering models) are a sub-class of the complementarity problem class, the cost minimization problem of the energy-systems models can be incorporated in an extended version of a computable general equilibrium model. (C.f., Böhringer (1998), and Böhringer and Rutherford (2008), see Section 6.1).

The **TIMES** model[2] is a generic model for the energy sector developed through an IEA implementing agreement, the Energy Technology Systems Analysis Program (ETSAP). The generic model is tailored by the input data to represent a specific region, ranging from global models down to single city models. The planning period is usually 20 to 50 years. The predecessor of TIMES is the **MARKAL** model.[3] MARKAL is used for the IEA's Energy Technology Perspectives reports (ETP) – published every second year. Much of the model structure is similar between MARKAL and TIMES, but TIMES allows the user to define more flexible time periods.

The **MESSAGE** model is another energy systems model, developed at the International Institute for Applied Systems Analysis (IIASA). It is part of IIASA's Integrated Assessment Scenario Analysis Framework. MESSAGE is a time-dependent linear programming model which provides an optimal allocation of fuels and energy carriers to meet a given demand. MESSAGE has a reference energy system (RES) that represents the most important energy carriers and conversion technologies. Energy demands are exogenous to the model. The general model characteristics are therefore very similar to TIMES and MARKAL.

## 3.3 Combining multiple modules: modelling systems

Large-scale modelling systems that are made up of several – soft and / or hard-linked – modules take a particular place in the spectrum of hybrid models. The National Energy Modelling System, **NEMS**, is developed by the Energy Information Administration of the US Department of Energy.[4] The primary use of the NEMS is to generate the projections in the Annual Energy Outlook.[5] NEMS is a linked modelling system consisting of several demand, supply and market modules. Most of these modules are bottom-up models, but some are top-down. Predecessors to NEMS are the PIES (Project Independence Evaluation System) and the IFFS (Intermediate Future Forecasting System) systems.

**PIES** is a combination of a linear programming model and econometric demand equations used to determine valid prices and quantities of fuels. The model solved for a supply-demand equilibrium in energy markets by iterating between the linear program and a reduced-form representation of end-use demand models. Shadow prices for fuels from the linear program were used as prices for end-user in each sector and region. The reduced-form demand representation was evaluated at these prices, the new end-use demands entered into the linear program, which was re-optimized. This iterative process continued until the end-use prices and demands were not changing between iterations, within a specified tolerance.

The NEMS model is solved by iterating through different modules in order to reach an equilibrium. Gabriel et al. (2001) argue that the problem could be modelled as a complementarity problem, and

---

the problem can be viewed as a game between different actors, where the objectives are competing and cannot be combined into a single common objective.

[2] TIMES is an acronym for The Integrated MARKAL-EFOM System.

[3] The name MARKAL is created from MARKet ALlocation model.

[4] https://www.eia.gov/forecasts/aeo/nems/documentation/

[5] http://www.eia.gov/forecasts/aeo/archive.cfm

thus implemented as an integrated hybrid model instead of a modular, linked hybrid model. However, the resulting mixed complementarity problem (MCP) would be too big to solve in acceptable time limits with the current state-of-the-art solution algorithms for MCP (i.e. PATH).

As such, already in its current form NEMS could benefit from more robust solution methods, as it regularly encounters convergence problems.

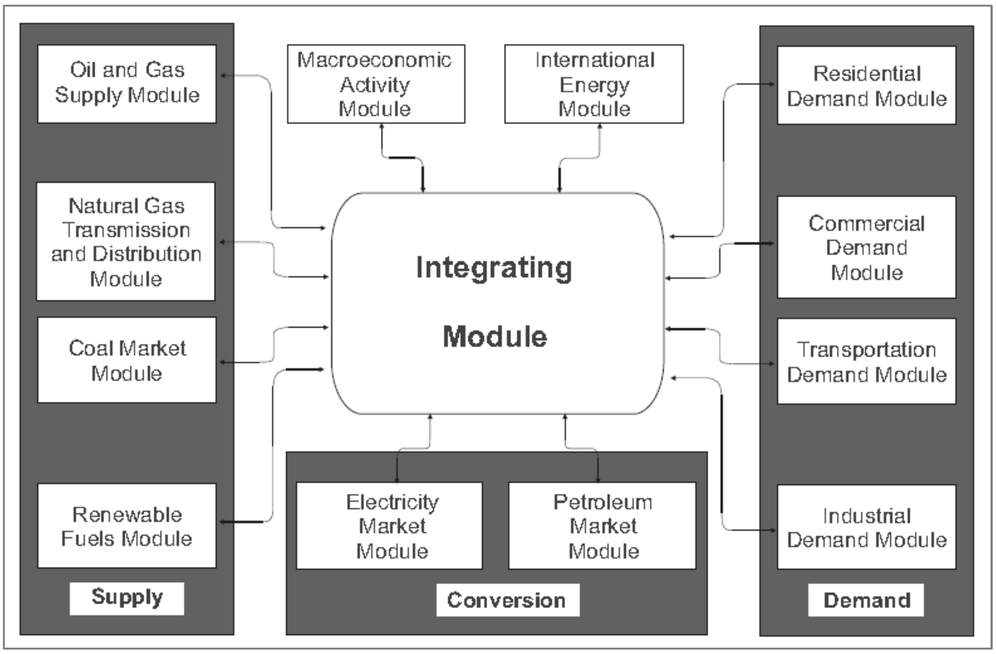



**Figure 3: NEMS - National Energy Modelling System**

Source: EIA DOE (2009) The National Energy Modeling System: An Overview[6]

The Canadian Integrated Modelling System **CIMS** is another example of a modular linked model that is solved by an iterative process. CIMS projects energy consumption in order to forecast greenhouse gas emissions caused by the combustion of fossil fuel products. CIMS combines the strengths of the top-down and bottom-up approaches. It has the technological richness of a bottom-up model, however it simulates technology choices by firms and households using empirically estimated behavioural parameters instead of portraying these agents as utility or financial cost optimizers. As such, it can be categorized as a behavioural simulation model.

CIMS' equilibrium solution is found by iterating first between energy supply and energy demand and subsequently between these components and the macroeconomic module. Changes in energy demand can result in changes in energy supply and consequently adjustments to energy prices, which in turn require updating energy demand for these new prices. Once energy supply and demand have reached an equilibrium, production cost changes may result in adjustments to demand for traded goods and services at the macroeconomic level, requiring additional iterations using these new demand levels. Given this simulation protocol, the more linked systems are integrated in a modelling system like CIMS, the more difficult it becomes to reach an overall equilibrium solution (*to converge*) (Jaccard et al., 2003a). This situation is quite similar to NEMS. (Murphy, Rivers et al. 2007) stated that alternative solving algorithms for CIMS will be explored when the model is expanded.

[6] https://www.eia.gov/forecasts/aeo/nems/overview/pdf/0581(2009).pdf (page 9)

## 3.4 Examples of energy sector – CGE model linkages

In the following (Sections 4 and 5), we present several examples of top-down bottom-up linked models with a focus on their modelling approach. Table 1 presents an overview of the examples.

**Table 1: Examples of linked models**

| Linked models | Data transferred from macroeconomic model | Data transferred from energy systems model | Link |
|---|---|---|---|
| **MARKAL-MACRO (1992)** | Energy demand | Energy costs | Hard |
| **MARKAL-MSG (1996)** | Useful energy demand | Energy mix | Soft |
| **MARKAL-MSG (2011)** | Demand for energy services.<br>Initial electricity production | Energy mix.<br>Electricity price. | Soft |
| **MARKAL-MSG (2012)** | Production and consumption quantities | Technology choices.<br>Tax increase giving higher present value of cost is transformed and allocated to sectors in MSG. | Soft |
| **MESSAGE-MACRO (1996)** | Energy demand | Prices (total and marginal) → quadratic demand functions | Soft |
| **MESSAGE-MACRO (2000)** | Demand curves for electric and non-electric energy | Energy shadow prices.<br>Energy demand.<br>Total energy system cost. | Hard |
| **MARKAL-EPPA (2005)** | Prices, taxes and transport demand | Adjustment of CES elasticities and AEEI | Soft |
| **TIMES-EMEC (2012)** | Energy demand (converted from monetary units) | Energy mix (to Leontief functions) | Soft |
| **Böhringer & Rutherford (2009)** | Energy demand | Net energy output.<br>Inputs of non-energy goods to the energy system. | Hard |
| **Abrell & Rausch (2016)** | Electricity demand and price.<br>Input prices for fuel, capital, labour, goods & services | Electricity dispatch.<br>Input demand for fuel, capital, labour, goods & services | Hard |

# 4 Approaches and Examples: Soft-linking[7]

The energy system models TIMES / MARKAL and MESSAGE (cf., Section 3.2) have frequently been used in model linking exercises. Most of these examples involve soft-linking. A large proportion of this literature describes applications for specific geographical regions. In the following, we briefly present some of examples.

[7] This section is largely based on Helgesen (2013)

## 4.1 MARKAL-MSG

MSG is a CGE model of the Norwegian economy developed in the early 1990s. MARKAL-MSG is an example of a soft-linked system (Johnsen and Unander, 1996). The user coordinates the data transfers in the following way:

1. Adjust exogenous demand assumptions in MARKAL (to reflect income effects)
2. MARKAL determines the cost-minimizing composition of the energy system.
3. Adjust the distribution of energy carriers in MSG-EE according to the results from the MARKAL calculations.

Johnsen and Unander (1996) investigated energy demand in the Norwegian residential sector. Not surprisingly, the feedback from MARKAL in this single sector had little impact on the general economy. Later, Martinsen (2011) soft-linked MARKAL and MSG to analyse technology learning. Endogenous technology learning is an option in MARKAL, using technology learning curves. Bjertnæs et al. (2012) also soft-linked MARKAL and MSG to analyse the effects on Norway of a national $CO_2$ tax and international $CO_2$ quota prices. Here, too, production and consumption from MSG are used as exogenous inputs into MARKAL; MARKAL then determines the technology choices.

## 4.2 MARKAL-EPPA

Schafer and Jacoby (2005, 2006) developed a hybrid CGE-MARKAL model focusing on transport. The CGE model is the Emission Prediction and Policy Analysis (EPPA) model. EPPA works on a macro scale, with a rougher, more aggregate sector classification than MARKAL. Being a CGE, EPPA is constructed on a social accounting matrix basis stated in (monetary) value terms, while MARKAL uses physical flows. A third model, of modal splits, is applied to connect the aggregate transport sector of the EPPA model to the technology detail in MARKAL.

The intermodal calibration needed is essentially one-way. EPPA is adjusted such that its transport sector mimics the subscale behaviour from the modal split model and MARKAL. The sector "own transport" needs factor inputs: vehicle manufacturing, and services and fuel. Normally the substitution elasticity between these inputs is constant in the EPPA model, but now the CES elasticity is adjusted according to the MARKAL results, and increases over time. Production of transport services is calibrated as well. In addition, modal splits are imposed and there is an overall calibration of the autonomous energy efficiency variable (AEEI) in EPPA from MARKAL. The AEEI for personal transportation is calibrated to yield an efficiency gain consistent with MARKAL. Simulation results from EPPA are fed to MARKAL. These data includes prices, taxes and transportation demand.

Convergence between the models is defined in terms of the total energy use in the transport sector. The results are scenarios at different levels of details that are consistent with one another at a more aggregate level. One consequence was that the substitution elasticities in the EPPA model had to be substantially tightened, in order to achieve a representation of the transport sector that was consistent with MARKAL.

## 4.3 TIMES-EMEC

EMEC[8] is a static CGE model, which has been developed and maintained at the Swedish National Institute of Economic Research (NIER) for over 10 years. EMEC and TIMES-Sweden have been soft-linked (Berg et al. 2012).

Some changes have been necessary to make the soft-link possible. In the production functions, the energy mix is modelled with Leontief functions instead of general CES functions, thereby fixing the proportions of energy based on the TIMES results. Also the household utility from energy to heating is changed to a Leontief representation. The mix is adjusted during the iterations, based on TIMES results.

When linking, the bottom-up model should receive the demand from the top-down model. There are some important differences in representations. The economic model calculates (monetary) *values*, but the engineering model material and energy *flows*. While values and prices are relative in the economic model, engineering models calculate absolute prices. Thus, demand in economic models is in (relative) *monetary* units and must be translated to *physical* units that are the representation basis in the engineering model. This is implemented by transferring relative changes instead of absolute levels. The energy mix is controlled by TIMES-Sweden, and the total demand is by EMEC.

Two other projects linking TIMES and a CGE models are HybCO2: TIMES to GEM-E3 for Portugal, and IntERACT, which links TIMES to a CGE model of Denmark. Both projects use prices from TIMES as input to the CGE model. Moreover, ETSAP has recently carried out the project "Linking TIMES and CGE models – Moving towards best practice".[9]

## 4.4 MESSAGE-MACRO

Wene (1996) soft-links MESSAGE and MACRO. MACRO receives costs/prices for energy supply from MESSAGE. From these MESSAGE supplies the quadratic demand functions for MACRO and the overall energy demand is adjusted. MESSAGE is re-run with these adjusted demands to give adjusted prices, etc.

Messner and Schrattenholzer (2000) brought the linkage between MESSAGE and MACRO further and introduced a hard-linked system. (See Section 5.3).

# 5 Approaches and Examples: Hard-linking

## 5.1 The decomposition method in the complementarity framework

The examples of soft-linking in Section 4 all involve energy system models based on an optimization approach (often linear programming). However, the development of specific and powerful solvers for complementarity models (i.e. PATH for GAMS) pushed the development of (mixed) complementarity (MCP) models not just for CGE models but also for bottom-up market equilibrium models. Using MCP models, both bottom-up and top-down have the advantage of being able to integrate the two models in a single formulation.

---

[8] Environmental Medium term EConomic Model

[9] http://iea-etsap.org/index.php/etsap-projects and http://iea-etsap.org/index.php/etsap-project/etsap-ucc-workshop

Böhringer and Rutherford (2008) present such an **integrated MCP** formulation of an energy market equilibrium within a top-down CGE model. Their model is stylized in order to present the general approach, and they also present illustrative policy simulations with this model for central energy policy issues.

However, when addressing real-world problems with large-scale models, a problem of dimensionality, or *numerical tractability*, quickly arises. As Böhringer and Rutherford (2009) discuss, the integrated model becomes too large and too prone for an "error in specification." (p. 1648), in particular when the energy model "includes upper and lower bounds on many decision variables." (p. 1649). Hence, Böhringer and Rutherford (2009) present a **decomposition** method for the formulation that permits a convenient combination of top-down equilibrium models and bottom-up energy system models. More precisely, they use the complementarity method to solve the top-down general equilibrium model and quadratic programming to solve the bottom-up energy supply model. Despite the practical innovation of this approach, it has remained challenging to implement and very few applications exist to date.

Abrell and Rausch (2016) apply this decomposition algorithm and develop a multi-country multi-sector general equilibrium model for Europe, integrating a high-frequency electricity dispatch and trade decisions. Their aim at studying the economic effects of energy policies such as electricity transmission infrastructure expansion and higher renewable energy penetration in Europe. With taking a focus on infrastructure, they have been the first to study the role of infrastructure for cross-country electricity trade in a general equilibrium context.

## 5.2 MARKAL-MACRO

There also exist hard-linking examples involving the MARKAL model. We will present two of them. Both MARKAL and MACRO are dynamic and assume perfect foresight. MACRO is an aggregate macroeconomic model for the entire global economy and is solved by nonlinear optimization. Input factors for production are capital, labour and different energy carriers. MACRO transfers energy demand to MARKAL. MARKAL determines the physical flows of energy for pre-specified exogenous demand levels, it determine the composition of the energy system that minimizes the energy expenditure. The energy supply costs (shadow prices) are transferred to MACRO. MACRO then updates the energy demand again. The data exchange is fully automated, such that is can be labelled as a hard-linked system. The linking ensures consistency between energy supplies, demands, and prices. Figure 4 exemplifies this: the left graph (A) shows that price and demand are related when MARKAL and MACRO are linked, whereas graph (B) does not indicate such a relation when MARKAL is run stand-alone.

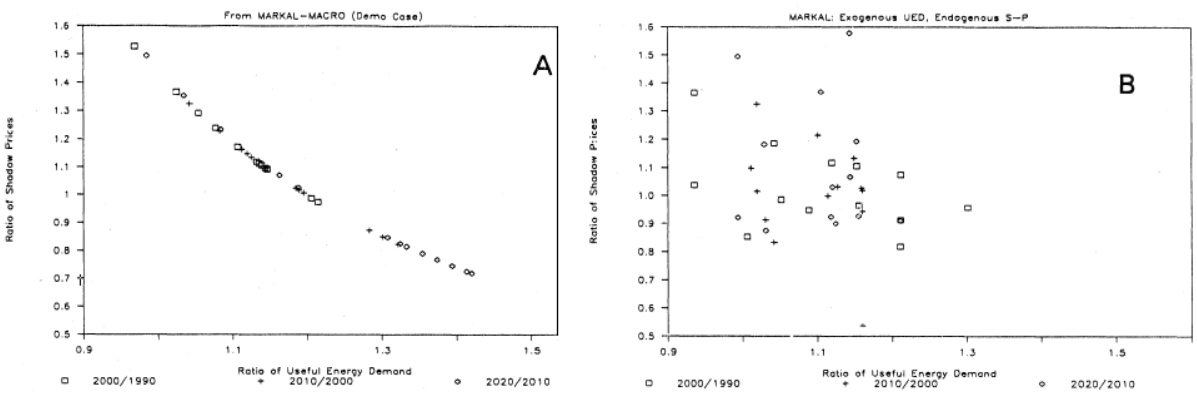



**Figure 4: Price-demand correlation in linked model (A) and stand-alone model (B)**

Source: Manne and Wene (1992), in Helgesen (2013)

Because MACRO includes substitution possibilities between energy, labour and capital, the solution space increases. As a consequence, final energy prices are lower in MARKAL-MACRO compared to MARKAL stand-alone. Issues that must be taken care of are, e.g., that energy supply costs for the MARKAL base year do hardly contain capital cost and therefore the shadow prices will not reflect long-term marginal costs for some demand categories. Applications using MARKAL-MACRO to analyse energy policies in China, Italy and the United Kingdom are Chen (2005), Contaldi et al. (2007), Strachan and Kannan (2008), and Strachan et al. (2009) respectively.

## 5.3 MESSAGE-MACRO

Wene (1996) soft-linked MESSAGE and MACRO. (See Section 4.4).

Messner and Schrattenholzer (2000) brought the linkage between MESSAGE and MACRO further and introduced a hard-linked system. MACRO defines an inter-temporal utility function to be maximized for a representative producer-consumer in each of the eleven world regions. The main variables are production factors such as capital, labour, and energy inputs, which determine the total output of an economy. The optimal quantities of the production factors are determined by their relative prices.

There are two categories of energy demand curves: electric and non-electric, for all time periods. Actual demands are determined by MACRO in a way that is consistent with projected GDP. MACRO also disaggregates total production into macroeconomic investment, overall consumption, and energy costs. A more recent example is given by Klaassen and Riahi (2007).

# 6 Approaches and Examples: Integrated models

Integrated hybrid models include functionality both from top-down and from bottom-up approaches. The choice for which sector(s) are specified *bottom-up* is driven by the research questions.

## 6.1 CGEs with bottom-up detail for a specific sector

As discussed above, the cost minimization problem of the energy-systems models can be incorporated in an extended version of a computable general equilibrium model. This leads to an integrated model. Böhringer (1998) has described such a model, and Böhringer and Rutherford (2008) have provided an approach for implementation.

Kulmer (2012) used a dynamic CGE to study the economic impacts of a carbon tax on Austrian transport sector. A bottom-up representation of passenger transport technologies is used and endogenous and directed technical change are included in the model as well.

# 7 Summary

Comprehensive evaluations of transitions in energy systems are subject to a central obstacle: When modelling the system with much technical precision and details, i.e. bottom-up , the changes in, and feedback from, macro-variables of the broader economic system are not accounted for. . However, when modelling from a top-down perspective to describe the macro-variables well, technical details are abstracted away and the model cannot be understood anymore as a consistent representation of the (technical) energy system.

The idea of *hybrid modelling* attempts to close the gap between the two approaches and to provide a framework that allows to evaluate overall economic developments with a sound engineering basis. A first step in hybrid modelling is *soft-linking*, i.e., models are run separately and the exchange of data is controlled manually. *Hard-linking* refers to an automated data processing and exchange. Lastly, *model integration* is the strongest degree of model-linking, i.e., the models are united into a single framework and solved as a whole, either in a single common run or using a decomposition algorithm.

The advantages of soft-linking can be summarized as practicality, transparency, and learning, while the advantages of hard-linking are efficiency, scalability, and control. Challenges when linking or integrating models concern the negotiation of common or overlapping input data and results, and scalability issues (especially relevant for complementarity problems). Applying a decomposition approach may prove an efficient solution in such cases. Lastly, the integration of models complicates the general handling, such as the model maintenance, which is why the degree of linking between models should be a conscious decision by the model developers and users.

# 8 References

Abrell, J. and S. Rausch (2016). "Cross-country electricity trade, renewable energy and European transmission infrastructure policy." Journal of Environmental Economics and Management 79: 87–113.

Berg, C., A. Krook-Riekkola, E. Ahlgren and P. Söderholm (2012). Mjuklänkning mellan EMEC och TIMES-Sweden - en metod för att förbättra energipolitiska underlag. Specialstudier. Sweden, Konjunkturinstitutet/National Institute of Economic Research: 73.

Bjertnæs, G., M. Tsygankova and T. Martinsen (2012) "The double dividend in the presence of abatement technologies and local external effects."

Böhringer, C. (1998). "The synthesis of bottom-up and top-down in energy policy modeling." Energy Economics 20(3): 233-248.

Böhringer, C. and T. F. Rutherford (2008). "Combining bottom-up and top-down." Energy Economics 30(2): 574-596.

Böhringer, C. and T. F. Rutherford (2009). "Integrated assessment of energy policies: Decomposing top-down and bottom-up." Journal of Economic Dynamics & Control 33(9): 1648-1661.

Chen, W. Y. (2005). "The costs of mitigating carbon emissions in China: findings from China MARKAL-MACRO modeling." Energy Policy 33(7): 885-896.

Contaldi, M., F. Gracceva and G. Tosato (2007). "Evaluation of green-certificates policies using the MARKAL-MACRO-Italy model." Energy Policy 35(2): 797-808.

Facchinei, F. and J. Pang (2003). Finite-Dimensional Variational Inequalities and Complementarity Problems, Springer.

Gabriel, S. A., A. J. Conejo, J. D. Fuller, B. F. Hobbs and C. Ruiz (2012). Complementarity Modeling in Energy Markets, Springer.

Gabriel, S. A., A. S. Kydes and P. Whitman (2001). "The National Energy Modeling System: A large-scale energy-economic equilibrium model." Operations Research 49(1): 14-25.

Helgesen, P.I. (2013): Top-down and Bottom-up: Combining energy system models and macroeconomic general equilibrium models. CenSES working paper 1/2013. http://www.ntnu.no/censes/working-papers

Hoffman, K. C. and D. W. Jorgenson (1977). "ECONOMIC AND TECHNOLOGICAL MODELS FOR EVALUATION OF ENERGY-POLICY." Bell Journal of Economics 8(2): 444-466.

Hourcade, J. C., M. Jaccard, C. Bataille and F. Ghersi (2006). "Hybrid modeling: New answers to old challenges - Introduction to the special issue of The Energy Journal." Energy Journal: 1-11.

Jaccard, M., Nyboer, J., Bataille, C., & Sadownik, B. (2003). Modeling the cost of climate policy: distinguishing between alternative cost definitions and long-run cost dynamics. The Energy Journal, 49-73.

Johansen, L. (1960). A Multi-Sector Study of Economic Growth, North-Holland Publishing Company, Amsterdam, Netherlands.

Johnsen, T. A. and F. F. Unander (1996). "Norwegian residential energy demand: Coordinated use of a system engineering and a macroeconomic model." Modeling Identification and Control 17(3): 183-192.

Jorgenson, D. W. (1982). An Econometric Approach to General Equilibrium Analysis. Current Developments in the Interface: Economics, Econometrics, Mathematics. M. Hazewinkel and A. H. G. Rinnooy Kan, Springer Netherlands: 125-155.

Klaassen, G. and K. Riahi (2007). "Internalizing externalities of electricity generation: An analysis with MESSAGE-MACRO." Energy Policy 35(2): 815-827.

Kulmer, V. (2012). "Directed Technological Change in a Bottom-Up/Top-Down CGE model: Analysis of Passenger Transport". Ecomod Conference Paper.

Manne, A. and C.-O. Wene (1992). MARKAL-Macro: A linked model for energy-economy analysis. Report BNL-47161, Brookhaven National Laboratory.

Martinsen, T. (2011). "Introducing technology learning for energy technologies in a national CGE model through soft links to global and national energy models." Energy Policy 39(6): 3327-3336.

Messner, S. and L. Schrattenholzer (2000). "MESSAGE-MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively." Energy 25(3): 267-282.

Murphy, R., N. Rivers and M. Jaccard (2007). "Hybrid modeling of industrial energy consumption and greenhouse gas emissions with an application to Canada." Energy Economics 29(4): 826-846.

Schafer, A. and H. D. Jacoby (2005). "Technology detail in a multisector CGE model: transport under climate policy." Energy Economics 27(1): 1-24.

Schafer, A. and H. D. Jacoby (2006). "Experiments with a hybrid CGE-MARKAL model." Energy Journal: 171-177.

Strachan, N. and R. Kannan (2008). "Hybrid modelling of long-term carbon reduction scenarios for the UK." Energy Economics 30(6): 2947-2963.

Strachan, N., S. Pye and R. Kannan (2009). "The iterative contribution and relevance of modelling to UK energy policy." Energy Policy 37(3): 850-860.

Wene, C. O. (1996). "Energy-economy analysis: Linking the macroeconomic and systems engineering approaches." Energy 21(9): 809-824.

SET-Nav
Strategic Energy Roadmap

| | |
|---|---|
| Project duration: | April 2016 – March 2019 |
| Funding programme: | European Commission, Innovation and Networks Executive Agency (INEA), Horizon 2020 research and innovation programme, grant agreement no. 691843 (SET-Nav). |
| Web: | www.set-nav.eu |
| General contact: | contact@set-nav.eu |

## About the project

SET-Nav aims for supporting strategic decision making in Europe's energy sector, enhancing innovation towards a clean, secure and efficient energy system. Our research will enable the European Commission, national governments and regulators to facilitate the development of optimal technology portfolios by market actors. We will comprehensively address critical uncertainties facing technology developers and investors, and derive appropriate policy and market responses. Our findings will support the further development of the SET-Plan and its implementation by continuous stakeholder engagement.

These contributions of the SET-Nav project rest on three pillars: modelling, policy and pathway analysis, and dissemination. The call for proposals sets out a wide range of objectives and analytical challenges that can only be met by developing a broad and technically-advanced modelling portfolio. Advancing this portfolio is our first pillar. The EU's energy, innovation and climate challenges define the direction of a future EU energy system, but the specific technology pathways are policy sensitive and need careful comparative evaluation. This is our second pillar. Ensuring our research is policy-relevant while meeting the needs of diverse actors with their particular perspectives requires continuous engagement with stakeholder community. This is our third pillar.


## Who we are?

The project is coordinated by Technische Universität Wien (TU Wien) and being implemented by a multinational consortium of European organisations, with partners from Austria, Germany, Norway, Greece, France, Switzerland, the United Kingdom, France, Hungary, Spain and Belgium.

The project partners come from both the research and the industrial sectors. They represent the wide range of expertise necessary for the implementation of the project: policy research, energy technology, systems modelling, and simulation.